Modeling and Validation of the Effects of Sound on the Marine Environment

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LONG-TERM GOALS

The long-term goals are to develop novel techniques to measure and predict, through modeling, the effect of sound on the marine environment. Modeling includes acoustic sources, propagation and the interaction of sound with animal behavior models. Determining the necessary environmental information such as bathymetry, sound speed and seabed properties for accurate modeling is also an essential component of this work.

OBJECTIVES

The objective of this research is to develop modeling tools for estimating the impact of sound on marine life and to validate this modeling effort with measurements. The goal is to provide state-of-the-art, open source codes to model sound sources, sound propagation and animal behavior. We will also assemble open source environmental databases for quantities such as seabed properties, bathymetry and ocean sound speed. Together, these tools will provide the best estimate of the impact of various sonar systems on the marine environment. These tools are bundled with a simple user interface in the ESME Workbench and are intended to be a type of gold standard for estimating impact. Currently, Navy environmental impact statements are prepared at the Naval Undersea Warfare Center (NUWC) and by several government contractors. The software and databases being used are often either classified or proprietary. ONR has put together a team consisting Boston University (David Mountain), Biomimetica (Dorian Houser), HLS Research (Michael Porter) and Portland State University (Martin Siderius) to build the ESME Workbench which will make the needed calculations for assessing environmental impact without using classified or proprietary components. In 2009 there were three main areas of research, 1) Quantifying different methods for modeling sonar impact. 2) Validation and verification of the ESME Workbench propagation modeling algorithms and 3) Developing a surrogate marine mammal for measuring ocean acoustic signals using a hydrophone integrated on a sea glider.

APPROACH

Comparison of current methodologies for preparing impact statements
Environmental Impact Statements (EIS's), are currently prepared in several places both within the government and through contractors. Two different analysis methods have emerged which estimate the impact of various sonar operations on marine mammals. The first is commonly referred to as the static

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distribution method. Here, each species has a statistical distribution in range, bearing and depth which is generally derived from collected data. The second method uses simulated animals (animats) which are randomly distributed in an area of interest and their swimming behavior is simulated over time. The question being addressed here is, "Do EIS's prepared using these two methods produce the same result?" To determine this a study was conducted to compare the two methodologies:

1. **Static Distribution**: This method accounts for a species location in depth by assuming a particular diving behavior for the species. The animal's statistical distribution in depth is generally derived from collected data or using a data driven animal movement model such as Biomemtica's 3MB.

2. **Animats**: Using Biomemetica's 3MB software [1], animals (animats) are randomly distributed in an area of interest and their swimming behavior is simulated over time. Using each animat position, with respect to time, the animat's accumulated sound energy exposure is determined as well as its maximum received sound pressure level.

Comparisons between the animat and static distribution methods were made based on a generalized, range-independent environment. This simple environment allows us to study the effects the methodologies without excessive computation time. The ray/beam code Bellhop [2,3] was used as the acoustic propagation model with the environmental parameters scenario dependent. An animal density of 0.01 animals per square km was chosen for the simulation studies. For the static distribution method, the densities were made to be uniform and static in range (across the surface), with a depth distribution. For the animat approach, multiple realizations of 100 animats were used to obtain reliable averages and standard deviations. That is, to "average out" the effects of any particular random animal distributions. The same source parameters were assumed for each simulation. A stationary omni-directional source was placed at the center of the box, with ping duration of 1 second and repetition rate of 30 seconds for a total of 120 pings/hr. The acoustic propagation was modeled using Bellhop with a source level of 235 dB (re 1 μPa) and a frequency of 3.0 kHz. A shallow diving and deep diving species were simulated. Results and comparisons between the static distribution and animat approaches are shown in the results section. Additional examples of useful comparisons might include variations of: species, sound speed profiles, bathymetry, source parameters and acoustic modeling methods.

For simplicity, the modeling and discussion in this report will be limited to Level B harassment due to behavioral disruption and in the absence of auditory fatigue. It will henceforth be referred to only as Level B harassment, or harassment. The number of harassments estimated to occur from an exercise involving MFA sources is calculated by evaluating a risk function that relates the risk of harassment to the maximum sound pressure level. The risk function varies between 0 (no risk) and 1 (maximum risk) and can be interpreted as the proportion of the time a given individual may alter its behavior in response to a given max SPL. This value can then be extrapolated to the population level.

Approach to ESME Workbench Validation and Verification
The ESME Workbench contains code written by programmers at Boston University. The software will ultimately serve as an open source code which can be easily learned and used by the scientific research community. The ESME Workbench has recently reached a level of maturity where it can be thoroughly tested by new users. The purpose of the testing is to put the ESME Workbench to use in a variety of simulation environments and to identify programming errors as well as to offer suggestions for improving the user interface. A series of test cases are being developed by the Portland State team to both insure the code produces correct results but also to provide users with a set of training examples.

Approach to development of a surrogate marine mammal for validation tests
The long term approach is to develop an acoustic sensor for deployment on a sea glider. The NEAR-Lab at Portland State owns a Webb Research Slocum Glider and is implementing a single hydrophone recording system on board. The hydrophone is a low cost, low power autonomous recording device using a commercial Gumstix CPU and a standard sound card. The system has been deployed successfully in a water tight bottle and now needs to be integrated into the science bay of the Slocum Glider. The system is shown in Fig. 1 below. This will provide a long endurance acoustic data collection system on a vehicle that is quiet and will record sound in the ocean while moving in range and depth much like a marine mammal.

A   B   C
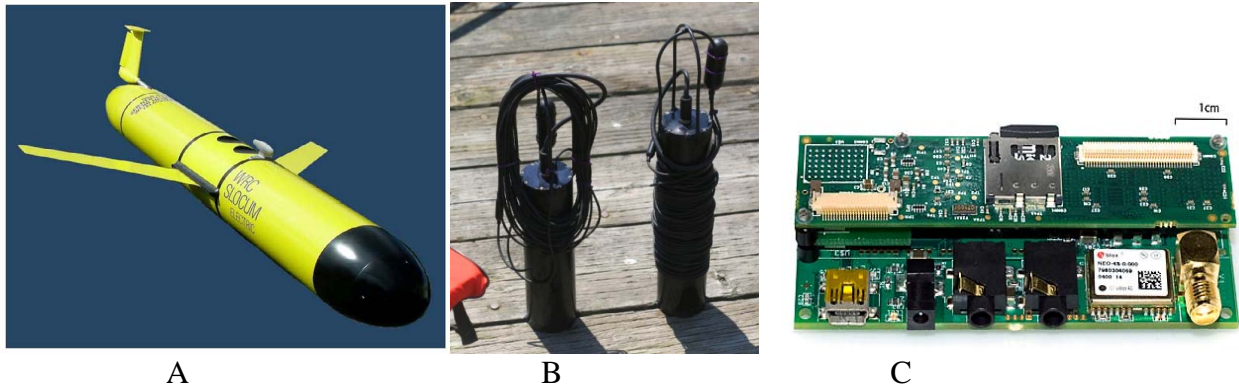
Figure 1. Panel A shows the Webb Research Slocum Glider. Panel B is the PSU developed autonomous sensor which will be integrated into the glider. Panel C is the Gumstix system used for data acquisition.

WORK COMPLETED

Work completed on comparison of current methodologies for preparing impact statements
We have completed a series of simulation studies to compare the different animal distribution methods for computing EIS's. The studies held all parameters constant except we changed the calculation of number of harassments depending on whether the static distribution method or animat methods were used. The results are given in the results section. We also believe this is a good framework for establishing metrics for making comparisons of other variables used in the impact statement development.

Work Completed on ESME Workbench Validation and Verification
The ESME Workbench version 2.1.1.798 was installed by research assistants in the Northwest Electromagnetics and Acoustics Research (NEAR) Lab at Portland State University.   Users loaded simulation environments and ran transmission loss (TL) calculations for a variety of scenarios and made notes of errors and/or suggestions for improving the software.   In addition, one of the research assistants validated the propagation modeling sub-routines by reproducing similar programming steps in MATLAB. In the process he was able to (1) verify the implementation of acoustic propagation algorithms and (2) validate that the algorithms were coded correctly (3) develop a test scenario that can be provided to new ESME Workbench users.

Work completed on development of a surrogate marine mammal for validation tests
The prototype sensor for autonomous hydrophone recording has been built and tested. This system will next be integrated on the glider. The glider has separately been tested and personnel trained on deploying and operating.

RESULTS

Results on comparison of current methodologies for preparing impact statements
Many different scenario can be contrived by varying the environments, changing source parameters and considering multiple species but some typical cases have been selected for illustrating the results. A simple example can be used to illustrate the differences between the static distribution and animat analysis methods. We begin by considering a 2-dimensional simulation space and calculating the number of harassments for a small population of animals by each of the methods. The simulation space is divided into two depth bins and two range bins, as shown in Fig. 2. We assume that an underwater sound source has a source level (SL, in dB re: 1 µPa) sufficient to produce a sound field with an SPL of 195 dB inside a surface duct (top depth bin in Fig. 2). Below the surface duct (bottom depth bin in Fig. 1 the SPL is 120 dB.   The sonar emits 2 pings, each with duration of 0.49 seconds. Thus, the total SEL is just below 195 dB and we do not have to consider harassment due to the onset of TTS. Two animats are in the first range bin during the first ping and they are both in the second range bin during the second ping.   However, between pings, the second animat moves down below the surface duct.
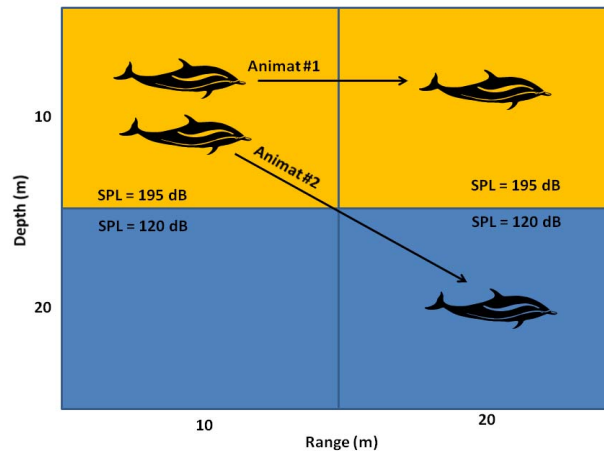

Figure 2: Illustration of the dive path for two animats in a simple 2 dimensional ocean environment containing a surface duct (shown in orange). The animat method considers both animats to be harassed due to their initial exposure to an SPL of 195 dB. For the static distribution method the space is divided into 4 quadrants; 2 range bins and 2 depth bins.

According to the animat method, both animats experienced a maximum SPL of 195 dB at some point in the simulation. Applying the risk function to this maximum SPL we find there is a 100% chance that animat #1 will be harassed (during either the first or second ping).   Likewise, from the risk function, there is a 100% chance that animat #2 will be harassed (due to the first ping). Thus, a total of 2 harassments are predicted to occur as a result of the scenario.

In the static distribution method the total number of animats is first distributed among the range bins. Since, there are two animats in the simulation space and two range bins; we will have on average 1

animat per range bin. Next, we consider the animal depth distribution: the animats are 75% in the top depth bin (surface duct) and 25% in the lower depth bin (below the surface duct). There are two range bins so in each the depth distribution is 75% in the surface duct and 25% below (or 0.75 of an animal in the duct and 0.25 below for each range bin). The chosen sound level for this example is simple since in the surface duct the probability of a take is 1 and below is 0. Therefore the number of takes is 0.75 times a probability of 1 or .75 takes. This is multiplied by the two range bins to give a total of 1.5 takes for this environment as compared to 2 takes for the animat method.

Case 1: Uniform Surface Duct
The first case is used to illustrate the two methodologies in a less contrived environment than the previous example. This three dimensional box ocean environment that extends 100 km x 100 km with a depth of 1 km. Four different dive patterns are considered and the differences between the static distribution and animat methods are evaluated. This first simulation is extremely simplified but is instructive to show how large differences in the results of the methodologies are possible.

For this simplified simulation the surface duct extends down to 100 m. The SPL within the duct is 173 dB everywhere in the duct, so that after 120 pings the total SEL is 194 dB (which is below the threshold for TTS). Below the surface duct, the SPL is 119 dB and (from the risk function) there can be no harassments.   The SPL in depth and range is shown in Figure 3.

One hundred animats are distributed in the ocean environment and randomly distributed across the surface of the box ocean environment with a distribution of 0.01 animats per square kilometer. The (horizontal) swim and (vertical) dive patterns are defined for each animat's coordinates and depth at 30 second intervals for 1 hour. For this simplified example, the dive pattern for all 100 animats is the same within a simulation, but the starting coordinates and horizontal swim pattern remain unique. Four different simulations are considered to demonstrate the resulting differences between the animat and static distribution methods. In each simulation, all 100 animats are given the same dive pattern. The four dive patterns are shown in Figure 4A and their corresponding depth histograms are shown in Figure 4B.
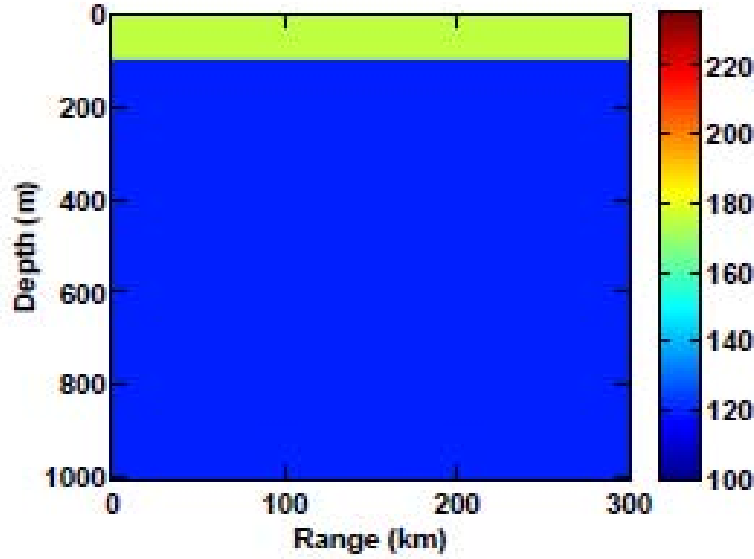
Figure 3. The sound pressure field (in SPL) from a source located at 0 km in range and 10 m depth in the box ocean shown in Figure 5 shows a uniform surface duct extending to 100 m depth. SPL values are mapped to the risk function for calculation of harassments in both the animat and static distribution analyses.
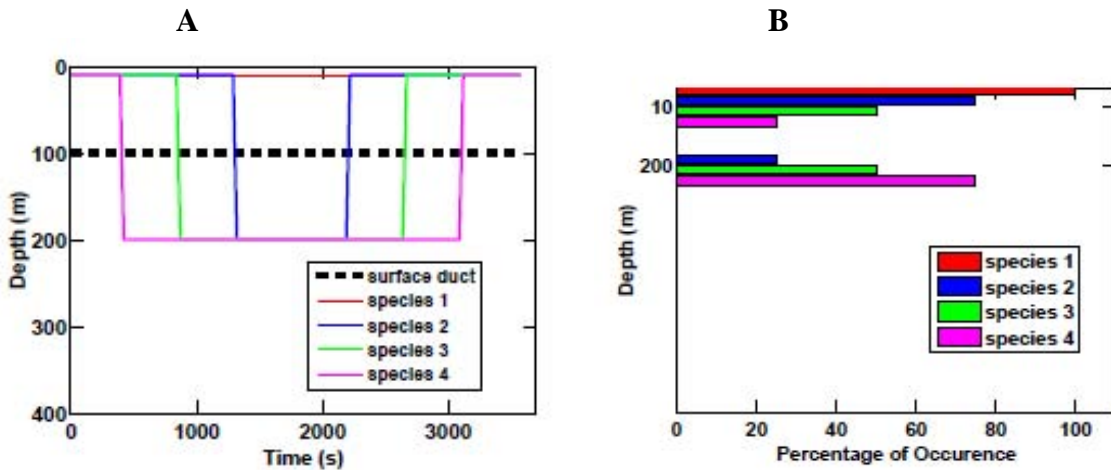

Figure 4. Panel A shows the simulated dive patterns for four artificial species in a surface duct used in the animat method. Species 1, 2, 3 and 4 stay within the duct (above 100 meters) 100, 75, 50 and 25% of the time, respectively, resulting in the depth histogram shown in panel B. The depth histograms are used in the static distribution method.

Each animat's coordinates and depths are extracted from the simulation and the maximum SPL corresponding to the overall dive profile is determined. The maximum received SPL value is applied to the risk function to find the "risk" of that animat being harassed. From Figure 4A it is apparent that in each of the four simulations, each of the 100 animats will be inside the surface duct at some point along

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its track, so each animat will receive an exposure of 173 dB SPL at least once during the simulation. Therefore, according to the risk function there is an 86.1% chance of each animat being harassed. Since there are 100 animats in the simulation the model arrives at a total of 86.10 harassments for each of the four simulations.

For the static distribution analysis, the 100 km x 100 km ocean surface is divided into 500 m x 500 m cells for a total of 40,000 cells. The model then applies the same animat distribution of 0.01 animats/km^2 to each of the cells (which have an area of 0.25 km^2) to get 0.0025 animats per cell. In the column below each cell, the 0.0025 animats are distributed according to the depth histogram for the corresponding scenario in Figure 4B. For each column in the box ocean, the SPL value at each depth is applied to the risk function to find the proportion of animals harassed at each depth. The proportion is applied to the population distribution to arrive at the number of harassments for every column. Summing all of the harassments from all of the columns gives the total number of harassments in the simulation space. The results are listed in Table 1 for comparison with the animat method.

Notice that in each case, the static distribution results are reduced from the animat results by the same percentage of time that the animats spend below the surface duct from the depth histograms in Figure 6B. This is because the static distribution method assumes that some percentage of animats remain below the duct for the entire duration of the simulation, while others are exposed to sound in the duct for the whole simulation period. The animat method more accurately accounts for each animat's exposure history as it travels in and out of the surface duct. Also, note that the results of the two methods are virtually identical for species 1. This is because its dive pattern does change in time. Therefore, it is possible for the two methods to agree in some scenarios. The 2% difference in this case was due to the spatial sampling of the animats. Smaller vertical bin sizes would lead to increased accuracy.

Table 1: Number of harassments for simulated dive patterns. The number of harassments in the static distribution method is reduced by the percentage of time the animats are below the surface duct shown in Figure 4A. The number of harassments in the animat method remains the same for all species because they all experience a max SPL of 173 dB (re: 1 μPa) at some point during their dive track.

Species	Animat Method	Static Dist. Method	Percent Difference
1	86.10	87.82	2.01 %
2	86.10	65.87	23.49 %
3	86.10	43.91	49.00 %
4	86.10	21.96	74.50 %

Case 2: AUTEC Sound Speed Profile
Next, we consider the same box ocean as Case 1 but with a realistic sound speed profile taken from a measurement at the AUTEC Navy range. For this scenario, Bellhop was used to calculate the incoherent TL from a 235 dB source at 5 meter increments in both depth and range. Marine mammal movements were simulated using 3MB. Two different species were evaluated independently. First, the shallow-diving marine mammal was considered. One hundred animats with individually distinct dive patterns were exported from 3MB and evaluated by both the animat and static distribution methods as was done

in case 1, above. Due to the randomized dive patterns of the animats in this scenario the simulation was repeated 50 times, and the number of harassments was evaluated for each realization. The average number of harassments is plotted in Figure 5 where the error bars indicate the standard deviation of the cumulative realizations.

The ability to account for the variability in predictions resulting from variations in animat behavior is a capability of the animat approach which is not readily apparent when implementing the static distribution method. Predictions of variability need not be limited to the standard deviation and other statistical approaches could be implemented. Whatever estimate of variability is used, the stabilization of the measure across multiple runs can be used to limit the number of times the Monte Carlo simulation must be carried out. Conversely, keeping record of the number of harassments across individual realizations permits the probability of maximum harassment events to be estimated. In combination with a measure of variability, both an estimate of the range of expected harassments and the potential for "spurious events" can be made. Such information would be beneficial to quantifying the uncertainty in impact estimates involving marine mammals and anthropogenic sound.
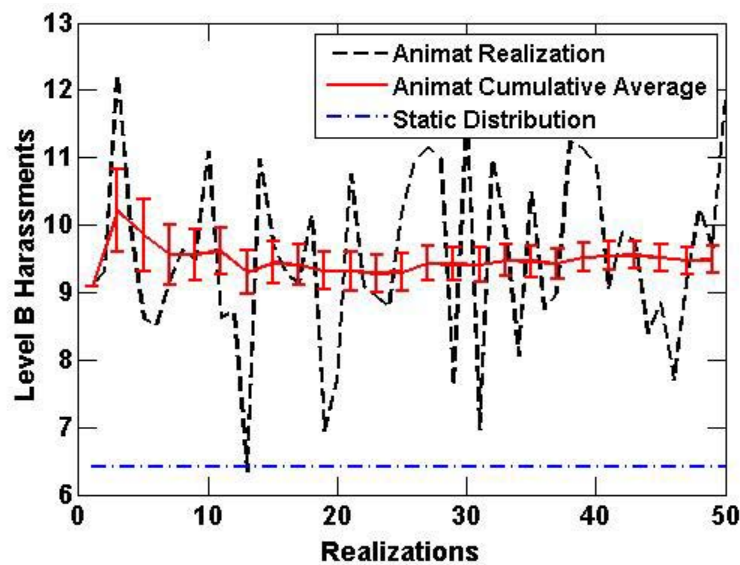

Figure 5. Number of harassments for a <u>shallow-diving species</u> in a 1 km deep ocean environment. After 50 realizations the animat method results in a mean of 9.54 harassments. Error bars indicate the standard deviation of the animat method. The static method arrives at a lower number of harassments.

For the static distribution method, the random dive patterns from all 5000 animats (100 animats x 50 realizations) were used to calculate the depth histogram. The animats were distributed into horizontal cells (500 m x 500 m) as in case 1, above, and then distributed into each column according to the depth histogram. The resulting number of harassments is plotted in Figure 5 for comparison with estimates obtained from the animat method. The number of harassments from each analysis method is also listed in Table 2.

Table 2. Number of harassments in a box ocean environment with 1km depth. The number of harassments in the static distribution method is lower than the animat method.

Species	Animat Method	Static Distribution Method	Percent Difference
Shallow-diving	9.54	6.42	48.60 %
Deep-diving	8.67	3.42	153.51 %

Note that the static distribution method produced a result that was 48.60% lower than the mean harassment estimate obtained by the animat method. Although in at least one of the 50 realizations the take estimate was similar to that obtained with the static distribution method, the harassment estimate of the static distribution method consistently underestimated the harassment estimates obtained with the animat method. In the worst case scenario, the estimate obtained via the static distribution method was half that estimated with the animat method.

A deep-diving animat species was also considered in this same ocean environment. Again, the animat method was repeated for 50 realizations. The final average after 50 realizations is listed in Table 2. Again, as in the shallow diving species, the static distribution method consistently underestimates the number of harassments estimated with the animat method. Similarly, the largest harassment estimate using the animat method is double that of the static distribution method.

Results on ESME Workbench Validation and Verification
A series of test cases are being developed to serve as sample cases for users of the ESME Workbench. Each of these test cases were reviewed and repeated using MATLAB routines. That allows a simple way to test the implementation of codes in the ESME Workbench while also providing users with test cases. Figure 6 shows and example test case being developed for a TL calculation for a transect done with the ESME Workbench.
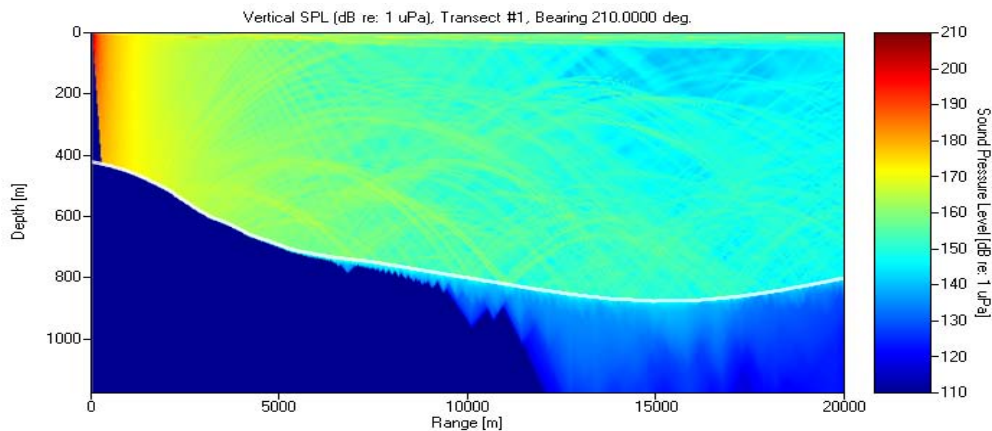

Figure 6. Test case developed for the ESME Workbench. Horizontal axis is range out to 20 km and the vertical axis is depth. The source uses typical settings for a mid-frequency active sonar without beampatterns.

IMPACT/APPLICATIONS

The analysis presented here demonstrate that the static distribution method of estimating Level B harassment of marine mammals consistently produces lower estimates than those produced by the animat method. Fundamentally, this occurs because the static distribution method forgoes the 4th dimension of the problem. It does not account for the occupancy of more than one sub-volume of ocean by individual animals. Marine mammals are dynamic in time and space and can traverse ranges and depths during military exercises or industrial activities that move them through multiple sub-volumes with differing levels of sound exposure. Although distributing animals in space is an idealized and intuitive approach to estimating sound exposure within a population of marine mammals existing in a region of anthropogenic acoustic activity, marine mammals are not "fractional." Implementation of marine mammals as distinct and individual entities in impact estimates provides a better approximation of the "real world" by accounting for the behaviors of individual animals in time and space.

The animat method additionally offers some benefits to the quantification of uncertainty. First, the ability to calculate variability in harassment estimates can provide regulators with better understanding of the potential impact to marine species. Second, the ability to determine a probability of a "spurious event," in which many marine mammal harassments may occur, can be calculated. Collectively, these pieces of information will better inform the regulator as to the potential for impact to marine mammals resulting from the introduction of sound into the ocean by human-kind.

Verification and validation efforts have been useful to insure the acoustic propagation algorithms in the ESME Workbench are implemented correctly. The procedure developed at PSU has been useful in revealing implementation problems at the early stages so they can be easily addressed. Programmers at BU developing the ESME workbench are notified when these issues occur and resolve them before future versions are released.

TRANSITIONS

None at this time.

RELATED PROJECTS

None at this time.

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